

# DUAL-LOOP OPTO-ELECTRONIC OSCILLATOR

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## Abstract

We describe and demonstrate a multi-loop technique for single mode selection in an opto-electronic oscillator. We present experimental results of a dual loop OEO free running at 10 GHz that has the lowest phase noise (-140 dBc/Hz at 10 kHz from carrier) of all free running room temperature oscillator to date.

## Introduction

The opto-electronic oscillators<sup>1-3</sup> (OEO) have many attractive properties<sup>4</sup> for microwave photonic communication systems, radar systems, and fiber optic communication systems. These properties include high spectral purity, high frequency generation capability, tunability, dual electrical and optical interfacing capability, and dual optical and electrical output capability.

The OEO consists of a pump laser and a feedback circuit including an electro-optic amplitude modulator, an optical fiber delay line, an photodetector, an electrical amplifier, and an electrical bandpass filter. Its oscillation frequency, limited only by the speed of the modulator and photodetector, can be up to 100 GHz.

In an OEO, many modes can oscillate in general. Single mode operation of the oscillator is established by including an RF filter in the loop to allow only one mode to oscillate while suppress other oscillation modes. Both of our theoretical and experimental studies indicate that the phase noise of the oscillator decreases quadratically with the loop delay time. Therefore increasing the OEO loop length is an effective way of reducing the oscillator's phase noise. Unfortunately for a sufficiently long loop, it is impossible to find an RF filter that is narrow enough to sustain single mode operation, for the mode spacing is the inverse of the delay time of the feedback loop. For example, for a loop length of 1 km, the mode spacing is 200 kHz and the filter bandwidth has to be on the order of few hundreds kilohertz. Such a narrow bandwidth is extremely difficult to obtain for a filter centered

at 10 GHz. In addition, the inclusion of a narrow filter in the loop scarifies the oscillator's tunability.

We present here a multi-loop technique that permits the OEO to operate in a single mode while having a long loop length, resulting in a reduced phase noise. It relaxes the requirement of bandwidth or eliminates the need of an RF filter in the loop, making the oscillator widely tunable. Furthermore, it reduces the oscillation threshold of the OEO by as much as 6 dB, reducing the gain requirement of the RF amplifier.

## Analysis

To illustrate the operation principle of the multiloop technique, a double loop OEO is shown in Fig. 1. Unlike a single loop OEO which only has one feedback loop, in a double loop OEO there are two feed back loops of different lengths. The open loop gain of each loop may be less than unity, however the combined open loop gain of both loops is larger than unity. For a double loop OEO, the possible oscillation frequencies must add up in phase after each round trip around both loops:

$$f_{osc} = (k + 1/2)/\tau_1 = (m + 1/2)/\tau_2 \quad \text{for } G(V_{osc}) < 0, \quad (1a)$$

$$f_{osc} = k/\tau_1 = m/\tau_2 \quad \text{for } G(V_{osc}) > 0, \quad (1b)$$

where  $k$  and  $m$  are integers,  $G(V_{osc})$  is the open loop voltage gain, and  $\tau_1$  and  $\tau_2$  are the loop delays of loop 1 and loop 2 respectively. From Eq. (1a) and Eq. (1b) one can see that if loop 2 is  $n$  times shorter than loop 1 ( $\tau_1 = n\tau_2$ ), then  $n$  must be an odd integer for the case that  $G(V_{osc}) < 0$  and an integer (even and odd) for the case that  $G(V_{osc}) > 0$ . The mode spacing is then dictates by the shorter loop:  $\Delta f = 1/\tau_2$ . On the other hand, the phase noise of the oscillator is dictated by the longer loop, resulting in an oscillator having large mode spacing and low phase noise.

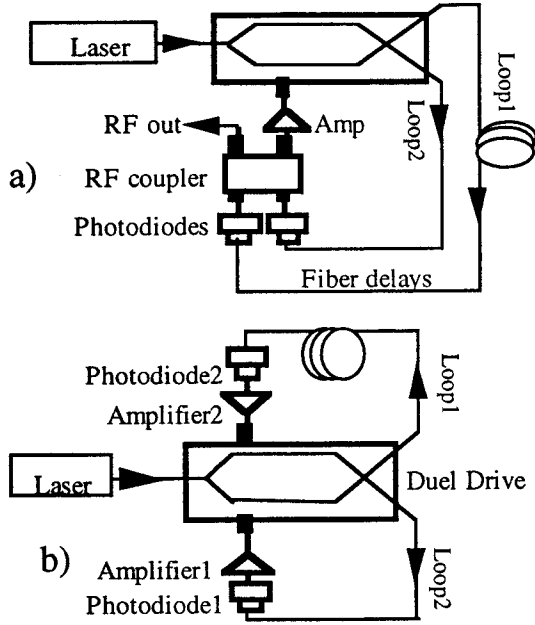


Fig. 1 Two example configurations of a double loop OEO.

The RF spectrum of the double loop OEO can be analyzed using the same quasi-linear theory developed for the single loop OEO.<sup>1</sup> Similar to the single loop OEO, the recursive relation for the double loop oscillator can be expressed as:

$$\tilde{V}_j(\omega) = (g_1 e^{i\omega\tau_1} + g_2 e^{i\omega\tau_2}) \tilde{V}_{j-1}(\omega), \quad (2)$$

where  $\tilde{V}_j(\omega)$  is the complex amplitude of the circulating field after a round trip,  $g_1$  is the complex gain of loop 1 and  $g_2$  is the complex gain of loop 2. The total field of all circulating fields is thus:

$$\begin{aligned} \tilde{V}_{out}(\omega) &= \sum_{j=0}^{\infty} (g_1 e^{i\omega\tau_1} + g_2 e^{i\omega\tau_2})^j \tilde{V}_j(\omega) \\ &= \frac{\tilde{V}_0}{1 - (g_1 e^{i\omega\tau_1} + g_2 e^{i\omega\tau_2})}. \end{aligned} \quad (3)$$

The corresponding RF power  $P(\omega) \equiv |\tilde{V}_{out}(\omega)|^2 / 2R$  is therefore:

$$P(\omega) = \frac{|V_0|^2 / 2R}{1 + |g_1|^2 + |g_2|^2 + 2|g_1||g_2|\cos(\Phi_1 - \Phi_2) - 2(|g_1|\cos\Phi_1 + |g_2|\cos\Phi_2)} \quad (4)$$

where

$$\Phi_i(\omega) = \omega\tau_i + \phi_i \quad i = 1, 2 \quad (5)$$

In Eq. (5),  $\phi_i$  is the phase factor of the complex gain  $g_i$ .

If the gain of each loop is less than unity, no oscillation may start independently in either loop. However, for the frequency components satisfying Eq. (1), oscillation can start collectively in the two loops. When Eq. (1) is satisfied, we have

$$\Phi_1(\omega) = 2k\pi \quad (6a)$$

$$\Phi_2(\omega) = 2m\pi \quad (6b)$$

$$\Phi_1(\omega) - \Phi_2(\omega) = 2(k - m)\pi \quad (6c)$$

Substitute Eq. (6) in Eq. (4) yields:

$$P(\omega) = \frac{|V_0|^2 / 2R}{1 + |g_1|^2 + |g_2|^2 + 2|g_1||g_2| - 2|g_1| - 2|g_2|} \quad (7)$$

In order for the oscillation to start from noise, we must have:

$$1 + |g_1|^2 + |g_2|^2 + 2|g_1||g_2| - 2|g_1| - 2|g_2| = 0 \quad (8)$$

For  $|g_1| = |g_2|$ , we obtain:

$$|g_1| = |g_2| = 0.5 \quad (9)$$

This is the oscillation threshold for the double loop OEO. If initially the small signal gain in each loop is larger than 0.5, the nonlinearity of the E/O modulator or the amplifier will bring the gain to 0.5 after the oscillation is started and stabilized.

Fig. 2 shows the calculated frequency spectrum of the double loop OEO from Eq. (7). In the calculation, we chose  $|g_1| = |g_2| = 0.5 - 10^{-8}$ ,  $|V_0|^2 / 2R = 1$ ,  $\tau_1 = 0.1 \mu s$ , and  $\tau_2 = 10\tau_1 = 1 \mu s$ . Fig. 2a shows the spectrum of an OEO of loop 2 alone, Fig. 2b is the spectrum of loop 1 alone, while Fig. 3c is the spectrum of the OEO with both loops present. The relative power of the vertical axis is the calculated power of each case divided by the calculated peak power of the double loop OEO. Note that the relative power for Fig. 2a and Fig. 2c are extremely low, due to the fact that the loop gain is too small for each loop to oscillate individually. For the double loop case of the Fig. 2c, a strong oscillation at selected frequencies is evident, with the mode spacing determined by the shorter loop and spectral width determined by the long loop, which agreed with our expectation.

Because of the relative large mode spacing, single mode operation of the OEO can easily be achieved by including a filter of relative wide bandwidth. Because  $\Delta f / f = -\Delta L / L$ , where  $f$  is the oscillation frequency,  $L$  is the loop length, and  $\Delta f$  is the frequency change caused by the

loop length change  $\Delta L$ , oscillation frequency of the double loop OEO can be more sensitively tuned by changing the loop length of the shorter loop. The tuning range is determined by the mode spacing of the shorter loop and the tuning resolution is determined by the mode spacing of the long loop. For example, if the short loop is 20 cm and the long loop is 10 km, the tuning range will be 1GHz and the tuning resolution will be 20 kHz. In practice, due to the mode-pulling effect, the tuning is rather continuous before hopping to a different mode of the long loop.

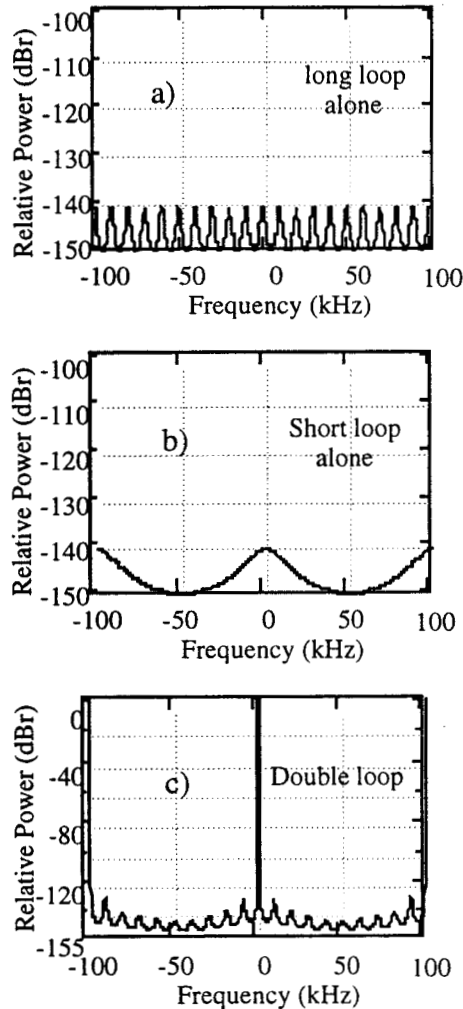


Fig. 2 Calculated spectra of a double loop OEO.

For a larger tuning range, a tunable RF filter can be used. However, the tuning of the center frequency of the filter should be synchronized with the tuning of the loop length, which tunes the oscillation frequency of the OEO. The combination of the double loop OEO and the tunable RF filter produces a novel frequency synthesizer with wide frequency tuning range

(tens of GHz), low phase noise, and high frequency resolution.

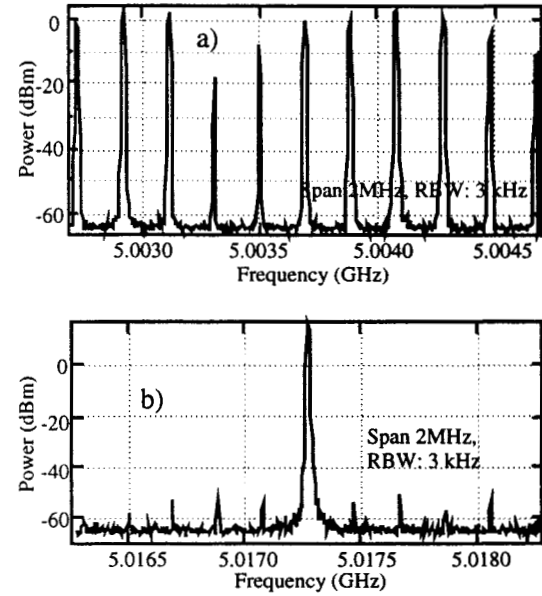


Fig. 3 Experimental results showing the effectiveness of the double loop mode-selection technique.

## Experiment

The double loop configuration depicted in Fig. 1b is used in the experimental setup. In the experiment, a dual drive electro-optic modulator was used. The shorter loop includes a photodetector and an RF amplifier. The longer loop (~ 1km in length) includes another photodetector, a filter centered at 5 GHz, and another RF amplifier. Fig. 3a shows the multimode oscillation of a single loop OEO in which the shorter loop is disconnected, however the longer loop is closed and its open loop gain is larger than unity. Fig. 3b shows the single mode oscillation of a double loop OEO in which both loops are closed and the gain of each loop was adjusted by inserting attenuators of proper values so that it was below the oscillation threshold. However, the combined loop gain for a particular mode was larger than unity. It is evident that the presence of the shorter loop effectively suppresses other modes of the longer loop and only leave one mode to oscillate. The mode suppression ratio is more than 60 dB. We find that even when the gain of each loop is larger than unity (each loop may oscillate by itself), the dual loop configuration is still effective in single mode selection. The side mode suppression ratio of more than 70 dB has been achieved.

It should be noted that an added advantage of the double loop configuration is that for a fixed

optical pump power, the second loop increases the open loop gain by 6 dB and hence lowers the oscillation threshold by 6 dB, making it easier to realize an OEO without employing an RF amplifier.

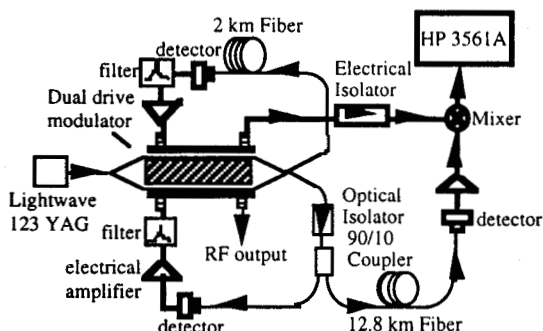


Fig. 4 Frequency discriminator setup for measuring the phase noise of the dual loop OEO.

We constructed another dual loop OEO with 2 km thermally stabilized fiber in the long loop and a filter centered at 10 GHz with a bandwidth of 40 MHz in each loop, as shown in Fig. 4. The spectra of the OEO output are shown in Fig. 5 and are compared with the spectra of a HP high performance RF synthesizer (model 8617B) for different spectrum analyzer settings. It is evident that the spectrum purity of the OEO is significantly better than the HP synthesizer.

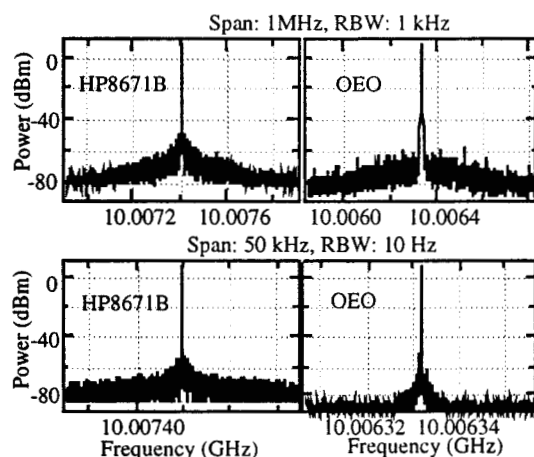


Fig. 5 Spectral purity comparison of an double loop OEO and a HP8671B synthesizer.

We used the frequency discrimination method to measure the phase noise of the double loop OEO and the experimental setup is shown in Fig. 4. In the setup, the reference fiber has a length of 12.8 km, significantly longer than the longer loop of the OEO. Both the loop fiber and the reference fiber are acoustically isolated in a box padded with lead-backed foam. Fig. 6 shows the measured phase noise as a function of offset

frequency. It should be noticed that at 10 kHz from the carrier (10 GHz), the phase noise of the double loop OEO is -140 dBc/Hz. As a comparison, we measured the phase noise of the high performance HP frequency synthesizer (HP8617B) using the same measurement setup shown in Fig. 4, however disconnecting the 2 km loop of the OEO at the RF input port to the modulator and then connecting the output of the frequency synthesizer to the RF input port. The result indicates that the synthesizer's phase noise at 10 kHz away from the 10 GHz carrier is about -96 dBc/Hz, more than 40 dB higher than that of the double loop OEO. By comparing the phase noise of the OEO with that of a free running sapphire loaded cavity (SLC) oscillator<sup>5</sup>, it is evident that the phase noise of the OEO is significantly lower than that of the SLC oscillator.

Fig. 6 also shows that the slope of the phase noise of the OEO as a function of the frequency offset is 30 dB/decade, about 10 dB/decade higher than predicted<sup>2</sup>. This is an indication that a 1/f noise source is present in the loop and has to be removed for better noise performance. This 1/f noise may come from the RF amplifiers used in the loop and can be removed with the carrier suppression technique.<sup>5,6</sup>

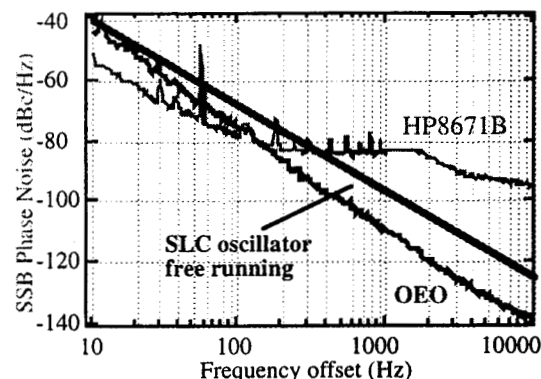


Fig. 6 Phase noise comparison of the OEO and other oscillators.

Finally, the Allan Variance of the OEO was measured to be  $10^{-10}$  at 1 second, which is consistent with that calculated from the measured phase noise at 1 Hz. We expect improved Allan Variance performance by reducing the close-in phase noise and stabilizing the temperature of the OEO.

We estimate that the ultimate stability of the OEO is on the order of  $10^{-14}$ . This estimation is based on our experimental investigation of the low thermal coefficient of delay (TCD) fiber commercially available. As shown in Fig. 7,

this fiber has a zero TCD around few degree C. Curve fitting the experimental data yields:

$$TCD = -1.5 \cdot 10^{-8} (T - T_0), \quad (10)$$

where  $T$  is the fiber temperature and  $T_0$  is the temperature at which the TCD is zero. On the other hand, the frequency stability of the OEO determined by the temperature fluctuation can be expressed as:

$$\Delta f_{osc} / f_{osc} = -\Delta T \cdot TCD. \quad (11)$$

Therefore one may obtain a frequency stability of  $10^{-14}$  if the fiber is stabilized to within 1 millidegree centigrade from  $T_0$ .

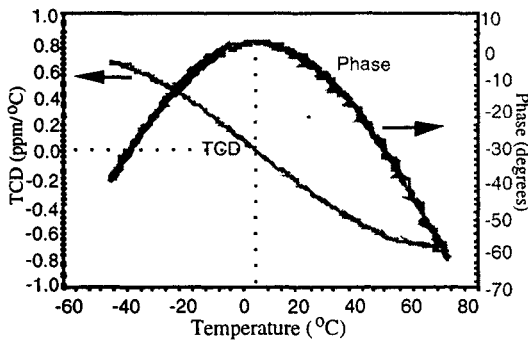


Fig. 7. Temperature dependencies of the thermal coefficient of delay of the low TCD fiber and the RF phase of a 0.5GHz signal transmitting through the fiber.

We also designed and built a temperature chamber, and demonstrated the feasibility of stabilizing a fiber spool of 2 km to within 1 millidegree centigrade.

### Summary

In summary, we have designed, built, and characterized a double loop OEO operating at 10 GHz. The free running OEO has achieved an unsurpassed low phase noise of -140 dBc/Hz at 10 kHz away from the carrier. Such a low phase noise oscillator can find wide applications in radar systems, microwave photonic systems, fiber optic communication systems, and high speed analog to digital conversion systems. The present frequency stability of the OEO is  $10^{-10}$  at 1 second. We anticipate, based on the

temperature stability of the low TCD fiber, that a ultimate frequency stability of  $10^{-14}$  can be achieved with OEO technology.

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